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Inflation of Kilauea Volcano Prior to Its 1967–1968 Eruption

Vertical and horizontal deformation give clues regarding the structure of an active Hawaiian volcano.

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The summit area of Kilauea volcano (Fig. 1) is a geodesist's nightmare. Bench marks shift their vertical and horizontal positions by as much as 50 or 100 centimeters from year to year, and the overall shape of the volcano is constantly changing. However, such ground deformation holds great promise for geophysicists because it yields important clues regarding the internal structure and functioning of the volcano.

Early in this century it was learned that the deformation of Kilauea was related to various stages of volcanic activity. Later it was found that the deformation follows a remarkably cyclical pattern. Typically, the volcano inflates gradually before an eruption and then deflates rapidly during an eruption or intrusive event that drains the reservoir system within the volcano. The long record relating Kilauean deformation cycles and eruptions strongly suggests that the inflation of Kilauea's summit is caused by the injection of basalt magma into an expanding system of underground reservoirs. Detailed knowledge of the inflation process is of vital importance if the overall functioning of the volcano is to be more fully understood.

Kilauea is an ideal subject for deformation studies. It is one of the world's most active volcanoes, and therefore it deforms frequently and rapidly. Because most of its eruptions are nonexplosive, studies can be carried out safely at close range during all stages of activity. The U.S. Geological Survey's Hawaiian Volcano Observatory is located at the rim of Kilauea caldera, so the tools and the manpower for detailed deformation studies are close at hand.

Techniques for monitoring Kilauea's inflations and deflations have steadily improved. Tilting of the ground was first detected in 1913 by deflections on horizontal pendulum seismographs operated at the newly established observatory (*1*). Leveling and triangulation measurements made between 1912 and 1927 showed vertical movements of about 4 meters and horizontal movements of about 1 meter in the area of maximum deformation (*2*). Eaton (*3*) greatly advanced the deformation studies in 1958 by introducing portable water-tube tiltmeters. With these inexpensive, highly sensitive instruments, ground tilts as small as 2×10^{-7} radian can easily and routinely be measured, and the deformation of Kilauea can therefore be monitored with greatly increased accuracy and speed. In 1964, Decker (*4*) first used a tellurometer and a geodimeter to measure horizontal deformation on Kilauea and clearly demonstrated that these instruments are capable of tracking the horizontal deformation that accompanies a typical Kilauean cycle of inflation and deflation.

Following the eruption of December 1965, members of the Hawaiian Volcano Observatory started to monitor the inflation of Kilauea in great detail. The standard techniques of precise leveling, measurement of ground tilt, and measurement of horizontal distance changes were used, and great emphasis was placed on both accuracy and speed. The need for accuracy is obvious. Speed is also an important factor because a protracted series of measurements at Kilauea, which is undergoing day-by-day deformation, is difficult to interpret. A brief description of the surveying instruments and techniques is given in Table 1.

The cyclical deformation of Kilauea during the past 8 years can best be portrayed with data from the tiltmeter, which is read daily at the Hawaiian Volcano Observatory, 2 to 3 kilometers from the centers of uplift (Fig. 2A). Since 1960, the periods of inflation have lasted from 2 to 22 months and have been punctuated by deflations that lasted from 12 hours to 6 months. The summit deflates during rift activity, but, interestingly, the tilt does not change appreciably during eruptions at Kilauea's summit. For example, the volcano continued to swell during and after the summit eruptions of February, March, and July 1961, and only a slight and temporary sudsidence of the summit was detected during the eruption of November-December 1959 and during the early part of the eruption that began in November 1967.

The east-west and the north-south components of tilt for the inflation that preceded the 1967–68 eruption are shown at larger scale in Fig. 2B. The inflation began just after the deflation and flank eruption of 24–25 December 1965 and continued uninterrupted for about 22½ months, until the summit eruption began on 5 November 1967. The general trend of the tilt curves is upward, but the details of the inflation were not simple. Both components of tilt rose at highly variable rates, and during some periods one or both components of tilt actually fell.

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In this study, emphasis was placed on the horizontal and vertical deformation and, to a lesser extent, on the results of the tilt measurements. The horizontal and vertical deformation, however, were monitored only periodically (Fig. 2B), and thus the continuous record of ground tilt provides a valuable indicator of the timing of important changes in the overall pattern of inflation.

Vertical Deformation

The bench marks of the summit level network are shown on the simplified geologic map of the Kilauea caldera region (Fig. 3). The westernmost bench mark, on the flank of Mauna Loa (stippled area), was used as an arbitrary point of zero altitude change; all altitude changes referred to in this article are relative to this point (5).

The total uplift that occurred from January 1966 to late October 1967 is shown in Fig. 4A; this total represents nearly all of the uplift that took place during the 22½-month inflation. The contours define a fairly simple dome-like uplift whose maximum change in altitude was about + 700 millimeters (relative, of course, to our arbitrary "zero"). It is obvious, however, that this area of uplift is not symmetrical

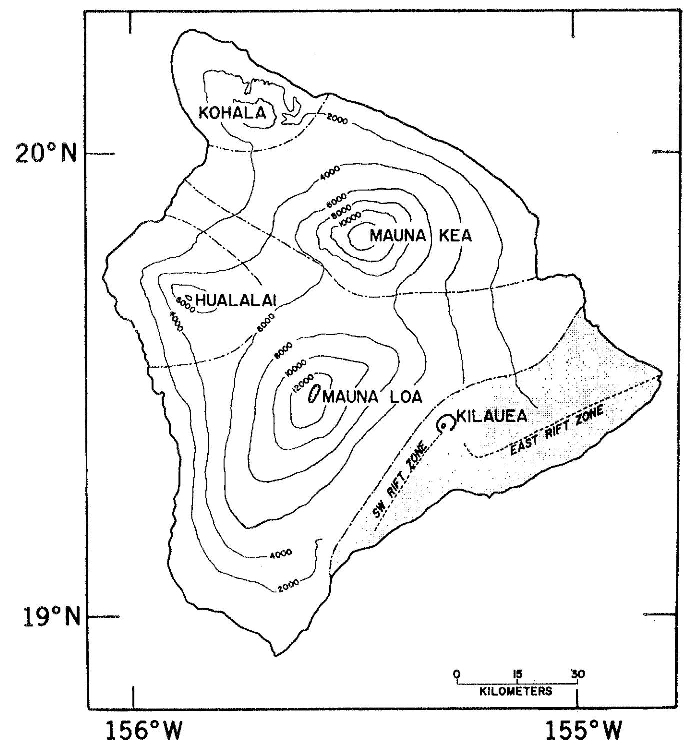
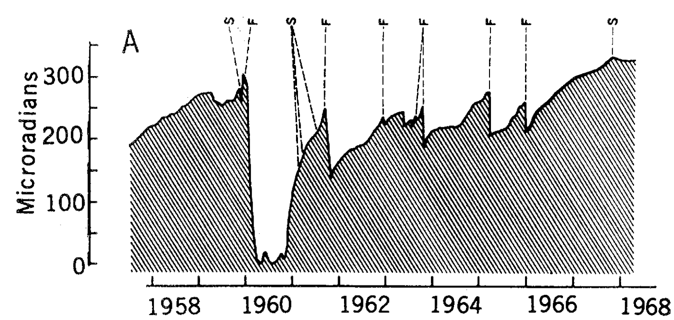
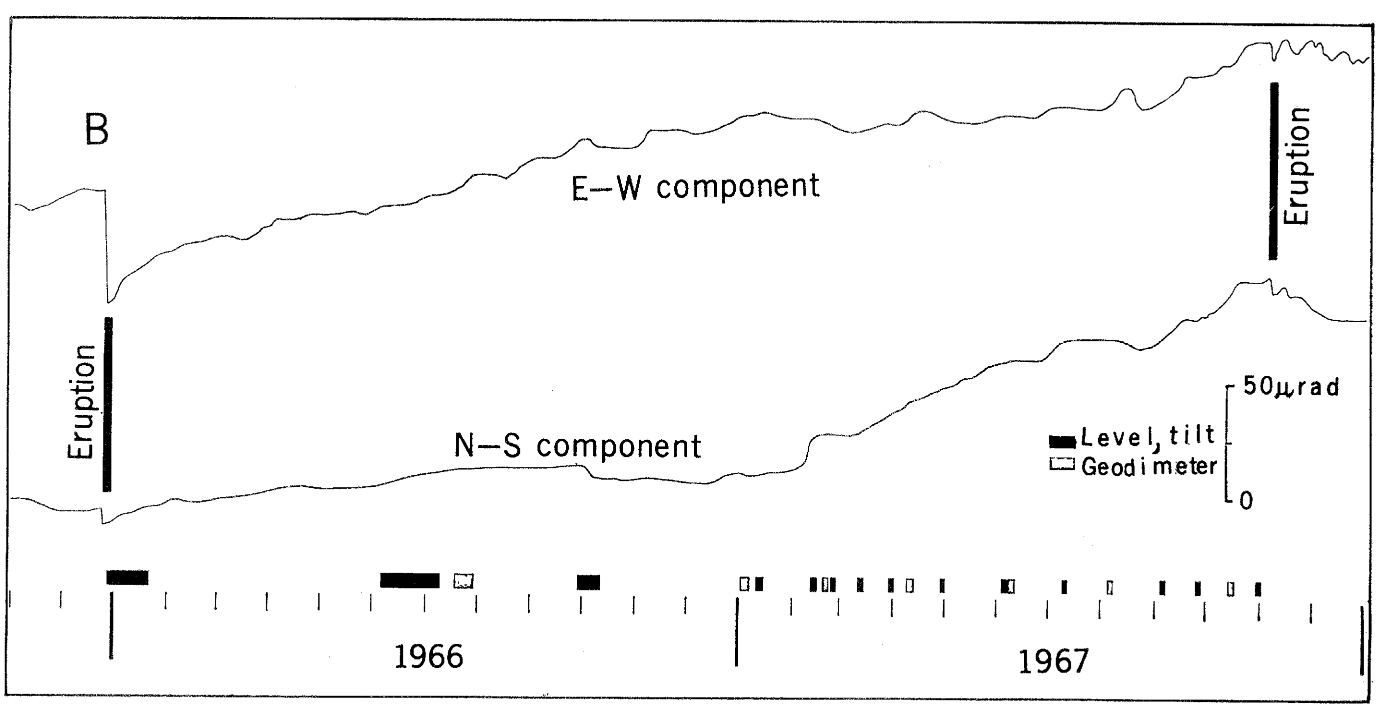


Fig. 1 (left). Index map showing Kilauea and the four other volcanoes on the island of Hawaii. Kohala and Mauna Kea have not erupted within historic times; Hualalai last erupted in 1801, Mauna Loa in 1950.

Fig. 2 (below). (A) East-west component of ground tilt recorded daily at the Volcano Observatory; rise of curves indicates inflation. *S*, summit eruptions; *F*, flank (east rift) eruptions. (B) Details of ground tilt prior to the 1967–68 eruption monitored at the Volcano Observatory. The timing of level, tilt, and geodimeter surveys is shown at bottom.



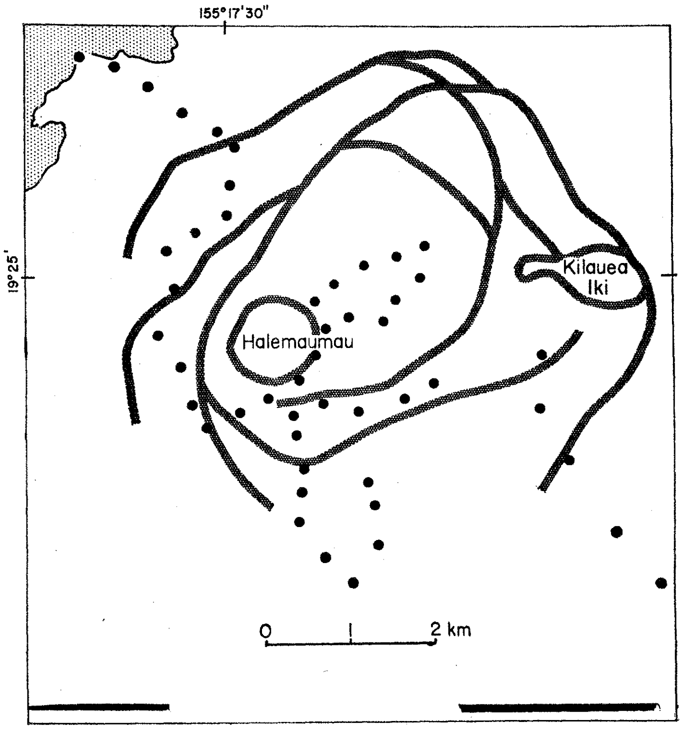


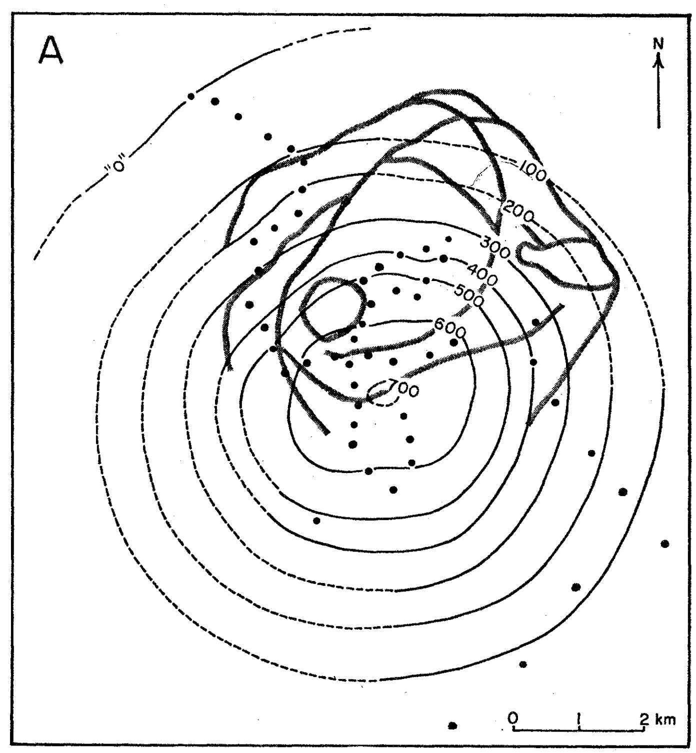
with respect to Kilauea's caldera; the center of maximum uplift lies a full kilometer southeast of Halemaumau (compare Figs. 3 and 4A) and clearly straddles the south margin of the caldera complex.

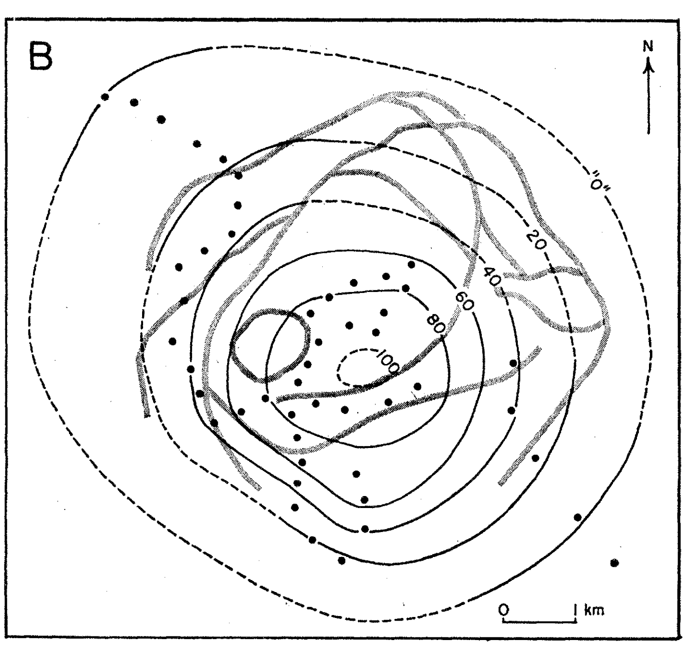
The simplicity of this overall uplift pattern should not be taken to mean that the inflation of Kilauea was a simple, orderly process. Thanks to our program of repeated leveling surveys, we were able to monitor the step-by-step progress of the uplift, and this uplift turned out to be anything but simple.

In the first 6 months of the inflation, from January to July 1966, more than 90 millimeters of uplift was recorded (Fig. 4B), centered about 1 kilometer east, or slightly east-southeast, of Halemaumau. During the next 3 months, from July to October 1966, the rate of uplift increased, and another 90 millimeters was added to the summit of Kilauea (Fig. 4C). Now, however, the uplift was centered northeast of Halemaumau, nearly 1 kilometer north of where it was centered during the first 6 months of 1966.

The center of uplift continued to migrate as the inflation progressed (Fig. 5A). It remained in the area east and northeast of Halemaumau only during







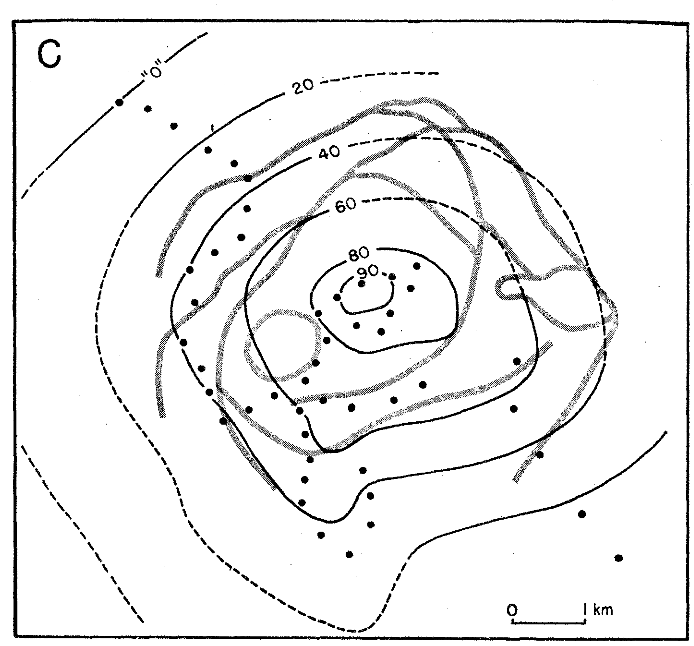


Fig. 3 (top left). Simplified geologic map of the Kilauea summit area. Heavy lines are main caldera faults; dots are bench marks of the summit level network. Reference bench mark lies at the edge of Mauna Loa volcano (stippled area) near the northwest corner of the map. [After Peterson (*13*)] Fig. 4 (top right and bottom). Changes in altitude at Kilauea's summit: (A) January 1966–October 1967; (B) January–July 1966; (C) July–October 1966. Caldera faults are shown by stippled lines; contours in millimeters.

Table 1. Deformation-monitoring techniques and their application at the Hawaiian Volcano Observatory.

Parameter measured	Instrument used	Methods for increasing efficiency and output	Measure of efficiency	Accuracy
Altitude change	Zeiss self-leveling pendulum levels, standard yard rods (invar strip)	Two crews run simultaneously. Most turning points nailed, and instrument set-up locations marked.	35 km of continuous leveling profile can routinely be run in 2 days.	Two loops, each about 3 km long, are routinely closed to within 6 mm (first-order accuracy). Remainder of network generally is not closed, and errors are uncertain, though probably small.
Ground tilt	Long-base water-tube tiltmeters	All three tiltmeters at a single station are read simultaneously. All hoselines at most stations are buried; this greatly reduces problems of thermal expansion.	A complete set of readings at one station can be made in 20 minutes, day or night.	2×10^{-7} radian
	Short-base water-tube tiltmeters	Tiltmeter mounted in underground vaults.	Can be read by one man in 3 minutes.	1×10^{-6} radian
	Continuously recording tiltmeter			3×10^{-8} radian
Change in horizontal distance	Model-6 geodimeter	Nine reflector prisms affixed in permanent array is standard reflecting unit.	25 lines of the summit network can be measured in 2 days.	Manufacturer's stated standard deviation per shot is $\pm$ (10 mm $\pm$ $2 \times 10^{-6} \times$ distance). Repeated measurement of calibration line gives greater accuracy, about $\pm$ 5 mm/1.6 km.

the period January to October 1966. In about 2 weeks in early October 1966 the center of uplift then moved swiftly to position 3, southeast of Halemaumau, more than 2 kilometers south of where it lay in July 1966. The center of uplift remained near position 3 for nearly 4 months, adding about 100 millimeters of uplift to the summit. Then in the span of only 1 week, in early February 1967, it changed its position from 3, through position 4, to 5. Leveling surveys in May 1967 and again in early June 1967 placed the center farther to the east, at positions 6 and 7, and then in about 10 days, in late June, the center changed rapidly from 7 to 8. A more gradual migration carried the center from 8 to 9 throughout much of July and August 1967, and the center made its final shift, in about 2 weeks in early October, from 9 to 10. The available data indicate that the center of uplift remained close to position 10 until the eruption began, on 5 November 1967.

Clearly, there is no simple explanation for this intricate pattern of uplift. It is apparent that the Kilauean summit is underlain by an extremely complex reservoir system instead of by a single chamber or reservoir. Moreover, the migration of the center of uplift suggests that successive regions within this reservoir system inflated in a certain order as the overall inflation proceeded. To further complicate the situation, the uplift did not take place at a uniform rate; instead, it occurred in surges, especially as the centers of uplift shifted rapidly from one position to another and new sites within the volcano began to inflate.

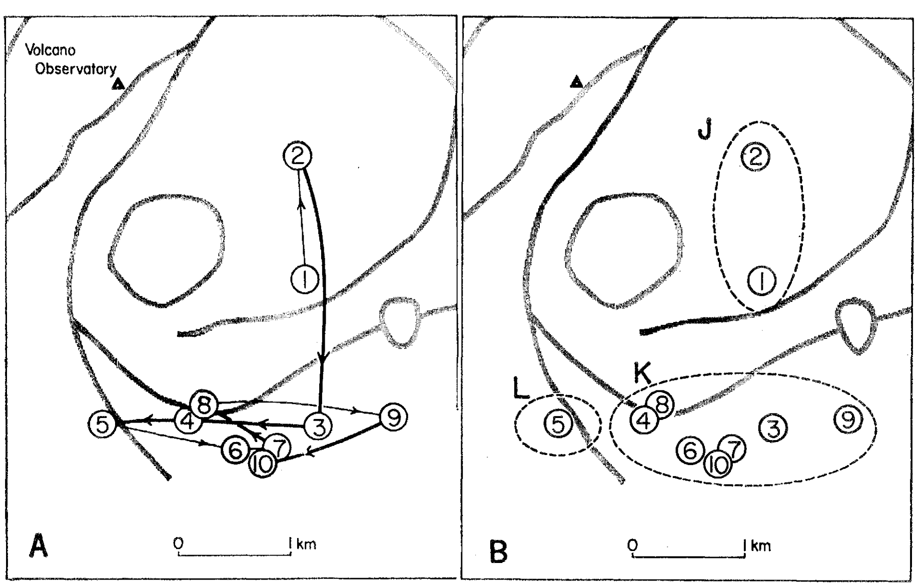


Fig. 5. (A) Centers of uplift determined by precise leveling: (1) January–July 1966, (2) July–October 1966, (3) October 1966–January 1967, (4) January–February 1967, (5) February–February 1967, (6) February–May 1967, (7) May–June 1967, (8) June–July 1967, (9) July–September 1967, (10) September–October 1967. Heavy lines indicate shifts in the center of uplift that took place in 2 weeks or less. (B) Dashed lines outline possible regions at depth that were inflated in the order *J*, *K*, *L*, *K*.

Little can be said about the precise location of Kilauea's reservoir system except that it lies somewhere beneath the south part of the summit caldera. One might suppose that the ten centers of uplift shown in Fig. 5A lie above discrete regions that were inflated, but for the most part this is not the case. Only about half of the leveling surveys were made just before or just after a shift of the center of uplift, so in most cases the leveling data provide only an integrated record of altitude change for rather arbitrary periods of time. However, approximate timing of the center shifts as well as the very approximate geographical location of the areas that were being inflated can be established with the help of the tilt data recorded daily at the observatory. For example, from January 1966 to mid-September 1966, the north-south component of tilt rose along a very smooth curve and the east-west component made only a few upward surges (Fig. 2B). This uneventful rise probably indicates that positions 1 and 2 of Fig. 5B lie above different parts of a single reservoir region (*J* in Fig. 5B) that was gradually inflated during the first 9 months of 1966. The 2-kilometer southward shift of the center of uplift in early October 1966, detected by means of the tilt data as it occurred, was an abrupt departure from this pattern and apparently represents the accelerated inflation of a new region within the reservoir complex. This new region (*K* in Fig. 5B) is drawn as an oval that includes seven of the centers of maximum uplift detected by precise leveling. Region *K* doubtless overlies an area of complex inflation; not only was it the site of greatest vertical deformation, but two abrupt shifts of the center of uplift took place within its boundary. Region *L* might simply be regarded as a western extension of *K*, but it is treated independently because the abrupt westward shift of the center of uplift in early February 1967 probably represents an important new extension of the actively expanding reservoir system.

An analysis such as this, however, gives us information only on the geometry of the reservoir complex in plan view. To get some idea of the depth of Kilauea's magma reservoir we must turn to a model that will relate vertical and horizontal movements at the surface of the ground to the increase in volume of a reservoir region at depth. Such a model has been provided by the Japanese geophysicist Mogi.

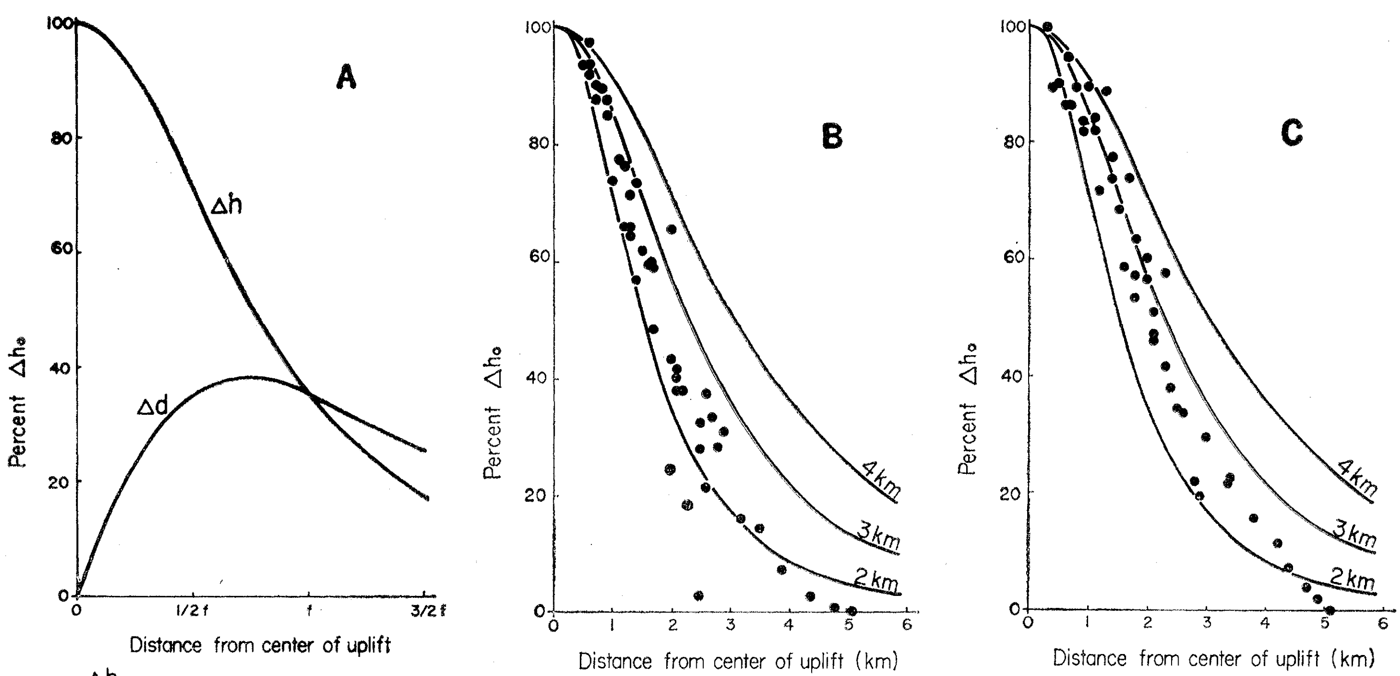
Table 2. Comparison of 2-, 3-, and 4-kilometer depth models as determined by the agreement between the theoretical and the measured length (in millimeters) of geodimeter lines. Degree of agreement is indicated by the number of lines in each of the categories—good, fair, and poor.

Depth model	No. of geodimeter lines in category: < 10 mm difference (good agreement)	10–25 mm difference (fair agreement)	> 25 mm difference (poor agreement)
	January–February 1967		
2-Km	13	6	1
3-Km	8	11	1
4-Km	5	8	7
	August–October 1967		
2-Km	3	7	11
3-Km	12	4	5
4-Km	5	7	9

Mogi's Model and the Third Dimension

Mogi (*6*) developed a model relating the horizontal and vertical displacements of the ground surface to the depth of a source of pressure. The model assumes that the earth's crust is a semi-infinite elastic body and that its deformation is caused by a small spherical source of hydrostatic pressure (a magma reservoir) whose radius is very small as compared with its depth. Figure 6A represents this model. The ordinate of the curves is the percentage of the maximum vertical uplift, which is determined by precise leveling. The abscissa scale is in units of *f*, the depth to the spherical source of pressure. As the depth is changed from model to model, the shape of the curve changes. For shallow source depths the curve is steep; it becomes flatter as the depth increases.

The shape of these curves is so sensitive to depth that various models can be tested simply by plotting the results of any given leveling survey directly on



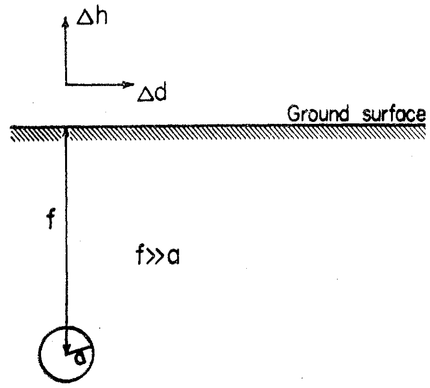
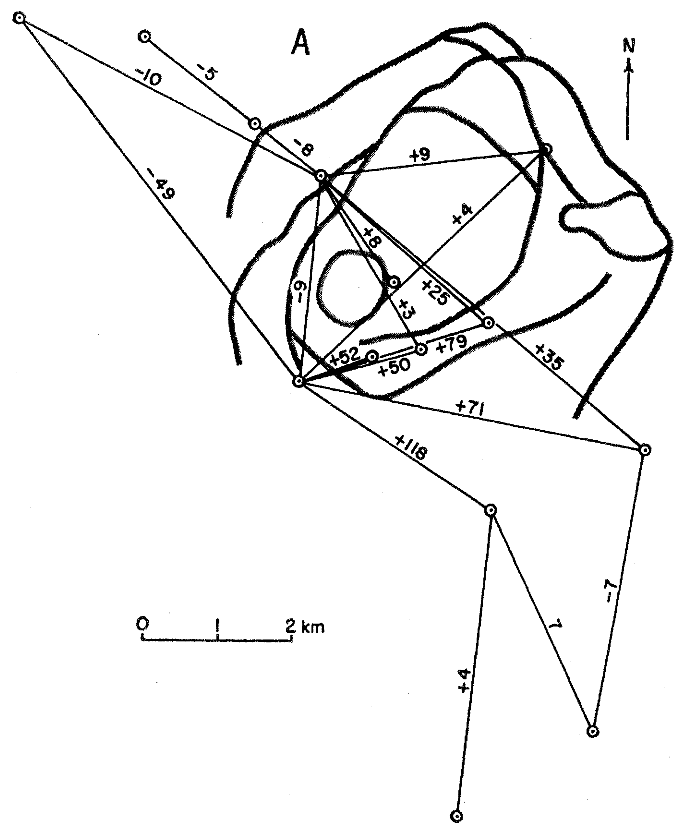


Fig. 6. (A) Theoretical vertical (Δh) and horizontal (Δd) displacement above a small spherical source of pressure at a depth *f*. Δh_o is maximum vertical displacement. [After Mogi (*6*)] (B) Vertical displacement of bench marks for the period January–July 1966; $\Delta h_o = 107$ millimeters. Most data points lie between the 2- and 3-kilometer curves. The reference bench mark (at a distance of 5.1 kilometers from the center of uplift) is assumed to be stable. (C) Vertical displacement of bench marks for the period August–October 1967; $\Delta h_o = 160$ millimeters. Data points cluster near the 3-kilometer curve.



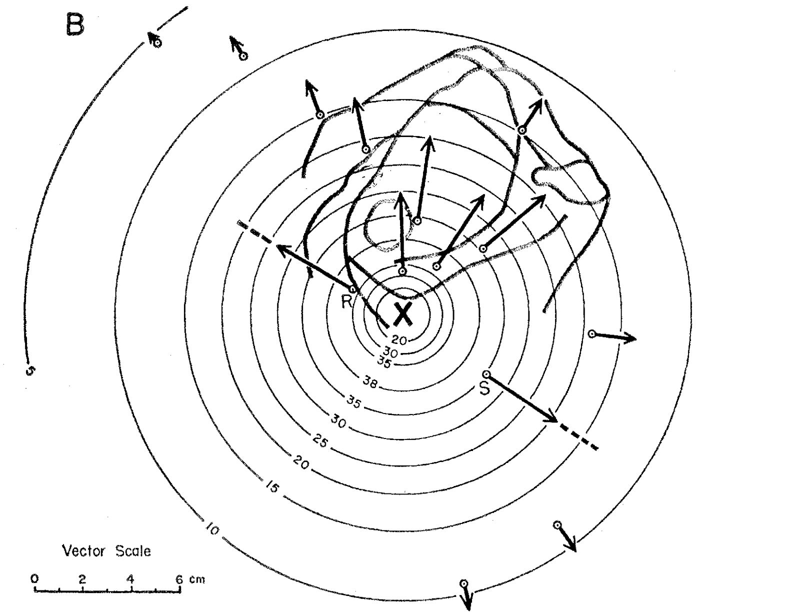


Fig. 7. (A) Change in length (millimeters) of 20 lines during the period 6 January to 21 February 1967. (B) Template (2-kilometer model) for determining theoretical radial displacement of points from the center of maximum uplift (X). Vectors show the theoretical displacements of the bench marks comprising the summit geodimeter network; the vectors originating at points *R* and *S* have been elongated (dashed lines) to make the extension between *R* and *S* equal to 110 millimeters. Contours in percentages; Δh_0 = 100 millimeters.

a family of depth curves. The data for January to July 1966 are plotted on the 2-, 3-, and 4-kilometer depth curves (Fig. 6B), and most of the data points fall between the 2- and 3-kilometer curves, perhaps somewhat closer to the 2-kilometer curve.

It must be remembered, however, that the reference bench mark at a distance of 5.1 kilometers from the center of uplift probably was uplifted 5 or 10 percent of Δh_0, not 0 percent as shown in Fig. 6B. If a proportional correction were made to all of the data points, they would still cluster between the 2- and 3-kilometer curves, but they would perhaps lie closer to the 3-kilometer curve. So, for the period January to July 1966, the first interval after the eruption of December 1965 during which vertical deformation was monitored, the data can be related to the inflation of a small spherical source at a depth of 2 to 3 kilometers.

The leveling data for August to October 1967 were plotted on the same type of graph (Fig. 6C); they fall close to the 3-kilometer curve. Preliminary interpretations of the data from other leveling surveys also suggest that the 3-kilometer model affords the best fit. Thus, if Mogi's model can be considered applicable to Kilauea, we conclude that the magma reservoir probably lies at depths of 2 to 3 kilometers, the overall average of the depth determinations being close to 3 kilometers.

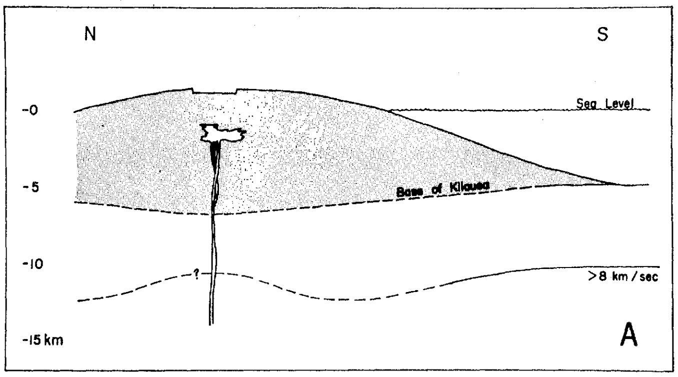
Horizontal Deformation

The ground surface near the summit of Kilauea expands as the volcano inflates, so it is reasonable to expect lines connecting points on either side of the active area of uplift to elongate—much as points on an inflating balloon move apart as the balloon grows larger. In an effort to monitor these horizontal changes, a network of 70 lines has been established and measured on Kilauea. Twenty of these lines cross parts of the main summit bulge and constitute the main summit network. This network was measured seven times between July 1966 and October 1967, and thus the horizontal deformation for more than two-thirds of the inflationary period has been monitored.

Direct measurements of the length of these lines were made with a model-6 geodimeter. The basic design and functioning of the instrument are described elsewhere (*7*). In essence they are as follows. A beam of visible light, modulated in turn at three separate, precisely controlled frequencies near 30 megacycles, is transmitted from the instrument to passive reflectors. Part of the reflected light returns to the instrument, where a phase comparison is made between the transmitted and reflected light beams modulated for each of the three frequencies. From the three phase differences so measured, the distance between the instrument and the reflector can be determined with great precision (Table 1).

Changes in length for 20 of the lines of the summit network for January and February 1967 are shown in Fig. 7A. All the lines crossing the area south and southeast of Halemaumau extended, and this, it should be remembered, is the area where the greatest uplift was taking place at that time. On the other hand, the lines extending radially outward from near the edge of the area of maximum uplift either shortened or extended by only small amounts.

One way to treat these data is to return to Mogi's simple model, which relates horizontal and vertical displacements. The curve for horizontal displacement (Fig. 6A), however, applies only to lines extending radially outward from the center of maximum uplift, but none of the lines in our geodimeter network extend radially outward from the center of uplift. Hence we must



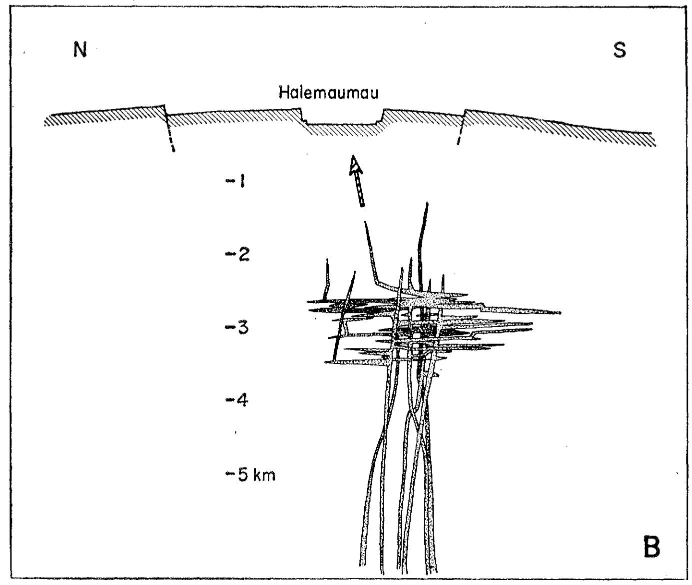


Fig. 8. (A) Cross section of Kilauea volcano showing the position of the magma reservoir lying 2 to 3 kilometers below the surface. (B) Larger-scale, highly speculative section of the magma reservoir. The arrow shows the possible path of magma as it erupted to the surface on 5 November 1967.

turn to a more general treatment of the model.

Mogi's curve for horizontal displacement was positioned with its origin at the known center of uplift for January and February 1967 and was rotated about this center, sweeping out a contoured surface. The surface in Fig. 7B, for example, was constructed from a curve for a 2-kilometer depth model. The theoretical radial displacement of any point can be determined simply by multiplying the amount of maximum vertical uplift (as determined by precise leveling) by the percentage given on the contoured surface. After the radial displacements of the end points of the measured lines have been determined, the theoretical extension or contraction of all the lines in the network can easily be obtained, graphically or analytically. However, the shape of the contoured surface is sensitive to the depth model used; the maximum contour of 38.5 percent lies farther from the center of uplift for deeper models than it does for shallower ones. The theoretical changes in the length of the lines are therefore clearly a function of the depth model used; by comparing the observed and theoretical changes for several depth models, a best fit can usually be obtained. This depth model should, of course, agree with the one obtained from the level data for the same period, and it does in the samples tested thus far.

For such an analysis, however, the position of the center of maximum uplift must be known. A contour map obtained from precise leveling outlines the general area within which the point of maximum uplift lies, but it does not pinpoint its exact position. This introduces uncertainty in positioning the zero point of the contoured deformation surface. In practice, contoured templates of the type shown in Fig. 7B have been prepared for various depth models, and the center of these templates is moved from position to position within the general area of maximum uplift until a point of best agreement between observed and theoretical changes is obtained.

Such an analysis has been made on the length changes monitored during January and February 1967. It soon became obvious that the line *RS* of Fig. 7B extended far more than could be explained by any simple model (the measured change was 118 millimeters, the theoretical change, 71 millimeters, for the 2-kilometer model). This line passes directly over the point of maximum uplift, and its abnormal extension suggests that the region close to the center of uplift deformed nonelastically in the horizontal direction. The vectors originating at points *R* and *S* have therefore elongated by the amounts necessary to make the "theoretical" extension of *RS* equal to 110 millimeters.

With this one modification, the vectors in Fig. 7B are those for the 2-kilometer model; other templates were used to test the 3- and 4-kilometer models. Table 2 shows that the change in length for 13 of the 20 lines was within 9 millimeters of that predicted by the 2-kilometer model. The agreement was poorer with the 3-kilometer model and was very poor with the 4-kilometer model. For this period, therefore, the model based on the assumption of a 2-kilometer depth to a locus of pressure change gives the best fit of the three models tested. This depth compares favorably with the 2- to 3-kilometer depth obtained from interpretation of the level data for the same period.

The geodimeter data for August to October 1967—the last pre-eruption period for which horizontal displacement data are available—were treated in the same way. After testing 2-, 3-, and 4-kilometer models, we found that the best agreement for the 21 lines measured is obtained with the 3-kilometer model (Table 2). A look at Fig. 6C shows that the level data for the same general period also suggest a 3-kilometer model.

It is noteworthy that, between August and October 1967, five of the lines crossing near the area of maximum uplift extended much more than would be predicted by any simple model of an inflating spherical reservoir, whereas the level data obtained during the same period show no radical departure from the model. Apparently, as the time of the eruption was drawing near, the volcano began to dilate far more than would be predicted by the model; it was literally being shoved apart as the pre-eruption inflation reached its final stages.

Four lines that cross near the area of maximum uplift accumulated average linear strains ($\Delta d/d$) of 1.3 to 1.4 $\times$ 10^{-4} between July 1966 and August 1967. Between August and October 1967 all these lines accumulated an additional strain of 0.3 to 0.4 $\times$ 10^{-4}, making the cumulative average strain on some lines nearly 2.0 $\times$ 10^{-4}. Japanese geophysicists working in the seismically active Matsushiro area have concluded that the ultimate strain of rocks there is on the order of 10^{-4}, and that strains beyond 10^{-4} are probably the result of nonelastic deformation, including fracture (*8*). Perhaps the ultimate strain of the rocks beneath Kilauea's summit area is about 1.5 to 2.0×10^{-4}. When strains greater than this accumulate, fracturing occurs, opening an avenue of escape for magma contained in the near-surface reservoir system. If the ultimate strain of Kilauean rocks can be determined, the field measurement of strain may well prove to be a useful tool in predicting eruptions.

The Reservoir

Interpretation of the leveling and geodimetering data suggests that the inflation of Kilauea's summit can be explained in terms of the expansion of a complex reservoir system at a depth of 2 to 3 kilometers. This depth places the reservoir well within the volcanic pile (Fig. 8A)—in fact, within the upper half of the volcanic pile.

If such a reservoir complex has existed throughout much of Kilauea's history, it is reasonable to assume that the reservoir has migrated to progressively higher levels as the volcano grew to its present size. Today's reservoir would, therefore, be underlain by the sites of former reservoirs, and these would probably consist of dense sills and feeder dikes, containing accumulations of olivine. The presence of these materials would produce a roughly cylindrical zone of high specific gravity, extending to unknown depth, and this probably explains part of the large positive gravity anomaly associated with the summit of Kilauea (*9*).

Figure 8B is a highly stylized diagram of Kilauea's reservoir. We, of course, do not know the exact configuration of the reservoir system, but we have depicted it as a plexus of sills and dikes in an intricate intrusive relationship. It is thought that sills are an important element of the reservoir complex because they are common in the upper 300 meters of the Kilauean pile that is exposed in the walls of Kilauea crater and Halemaumau. Moreover, most of the interior of Kilauea is made up of gently dipping lava flows, and at least part of the expanding reservoir system at depth would, it seems reasonable to suppose, seek out these flat-lying zones of weakness to form sills.

Doubtless thousands of steeply dipping dikes are also clustered in and near the reservoir. Dikes and other steeply dipping conduits must connect the shallow reservoir system with the deeper magma source, and other dikes have at times connected the reservoir with eruptive fissures at the surface. By analogy with the sills, it seems likely that the expanding reservoir also utilizes these steeply dipping zones of weakness as it grows larger. In fact, the anomalously large extensions of the geodimeter lines crossing the area of maximum uplift may well be explainable in terms of expanding dikes at depth.

We have implied, up to this point, that Kilauea volcano has only one magma reservoir. This may be the case, but recently gathered data demand that we consider the possible existence of other underground areas of magma storage. From January 1966 to October 1967, precise leveling was extended southeastward from the summit area of Kilauea along lines both parallel to and perpendicular to the upper east rift zone (Fig. 1). During almost every leveling period, uplift was detected in the area near Makaopuhi Crater, 12 kilometers southeast of Halemaumau, and this uplift amounted to about 21 centimeters during the 22½-month inflation. The data are insufficient for outlining this area of uplift on a map, but it clearly forms a discrete bulge separated from the main summit uplift. The depth to this possible reservoir is not known, but the rather small surface diameter of the anomaly (perhaps 4 kilometers) suggests that it is a shallow feature lying within a few kilometers of the surface. The existence of an underground fluid connection between this possible reservoir area and the main summit reservoir cannot be proved, but such a connection is strongly suggested by the consistent uplift of both areas during the 22½-month inflation.

Of perhaps greater interest is the possibility that another magma reservoir lies at some greater depth beneath the shallow summit reservoir (2 to 3 kilometers deep). Analysis of level data for the period 1921 to 1926 led Mogi (*6*) to postulate a spherical source of pressure change at a depth of 25 ± 5 kilometers below the summit of Kilauea (in addition to the shallower one he postulated at a depth of 3.5 kilometers). Later, doubt was cast upon the existence of the deeper source because of possible error in the length of the rods used during the 1921–26 level surveys (*4, 10*).

Some unexplained facts remain, however. Kilauea summit inflated at a variable rate during the period January 1966 to October 1967; during much of the inflation the ground tilt monitored at the Volcano Observatory changed at very low rates, but at other times, especially when the center of uplift was changing its position, the tilt rates were much higher. From this we have inferred that magma was rising from depth into the shallow reservoir system at a variable rate. Eaton (*11*) estimated that magma is generated within the upper mantle at depths of 45 to 60 kilometers beneath Kilauea, but it is highly unlikely that the process of magma generation could be a start-and-stop process directly responsible for the variable rate of inflation of the summit reservoir. Temporary storage and irregular release of magma might take place in some other region—between, say, depths of 45 and 3 kilometers. One such possibility is a region near a depth of 30 kilometers. A distinct family of Kilauea earthquakes originates from this depth, whereas earthquake foci at deeper and shallower depths are rare. It may not be pure coincidence that the 30-kilometer depth agrees well with the 25-kilometer depth proposed earlier by Mogi.

The Final Minutes

Thanks to the continuously recording tiltmeter located at the Volcano Observatory, we were able to trace the inflation of Kilauea up to the very moment of eruption. The tilt was steady during the last several hours of 4 November and the first 1.5 hours of 5 November 1967. At about 01:33 on 5 November, strong harmonic tremor began recording on the seismographs near the summit, although no change in the tilt was detected. Shortly thereafter, at about 01:45, the tilt increased at a rate of about 0.75 microradian per hour—a rate greater than any recorded during the entire 22½-month inflation. A felt earthquake rattled through the summit area at 02:04, followed by another at 02:20. These two earthquakes originated about 4 to 5 kilometers below the summit of the volcano. If our estimates of depths to Kilauea's magma reservoir are reasonable ones, these earthquakes originated a full 1 to 2 kilometers below the magma reservoir. They, together with the accompanying harmonic tremor, were possibly caused by the sudden rise of new magma from depth into the shallow, highly swollen reservoir complex. Meanwhile, the tilt continued upward at its high rate. Within minutes, the reservoir could accept no more; magma forced its way upward, split north-south fissures across the floor of Halemaumau, and spilled onto the surface at 02:32 on 5 November, to begin the 1967–68 eruption (*12*).

References and Notes

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14. We thank the staff of the Hawaiian Volcano Observatory for invaluable aid and the staff of Hawaii Volcanoes National Park for logistical support. Publication of this article is authorized by the director of the U.S. Geological Survey.

Gene Regulation for Higher Cells: A Theory

New facts regarding the organization of the genome provide clues to the nature of gene regulation.

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Cell differentiation is based almost certainly on the regulation of gene activity, so that for each state of differentiation a certain set of genes is active in transcription and other genes are inactive. The establishment of this concept (*1*) has depended on evidence indicating that the cells of an organism generally contain identical genomes (*2*). Direct support for the idea that regulation of gene activity underlies cell differentiation comes from evidence that much of the genome in higher cell types is inactive (*3*) and that different ribonucleic acids (RNA) are synthesized in different cell types (*4*).

Little is known, however, of the molecular mechanisms by which gene expression is controlled in differentiated cells. As far as we are aware no theoretical concepts have been advanced which provide an interpretation of certain of the salient features of genomic structure and function in higher organisms. We consider here experimental evidence relating to these features. (i) Change in state of differentiation in higher cell types is often mediated by simple external signals, as, for example, in the action of hormones or embryonic inductive agents. (ii) A given state of differentiation tends to require the integrated activation of a very large number of noncontiguous genes. (iii) There exists a significant class of genomic sequences which are transcribed in the nuclei of higher cell types but appear to be absent from cytoplasmic RNA's. (iv) The genome present in higher cell types is extremely large, compared to that in bacteria. (v) This genome differs strikingly from the bacterial genome due to the presence of large fractions of repetitive nucleotide sequences which are scattered throughout the genome. (vi) Furthermore, these repetitive sequences are transcribed in differentiated cells according to cell type-specific patterns.

In this article we propose a new set of regulatory mechanisms for the cells of higher organisms such that multiple changes in gene activity can result from a single initiatory event. These proposals are presented in the form of a specific, relatively detailed model at the level of complexity which appears to us to be required for the genomic regulatory machinery of higher cells. We make no attempt to arrive at definitive statements regarding these proposed mechanisms; obviously evidence is not now available to support any model in detail. Our purpose in presenting an explicit theory is to describe the regulatory system proposed in terms of elements and processes which are capable of facing direct experimental test. It is hoped that our relatively detailed commitment will induce discussion and experiment, and it is expected that major modifications in concept will result.

Undoubtedly important regulatory processes occur at all levels of biological organization. We emphasize that this theory is restricted to processes of cell regulation at the level of genomic transcription.

We begin by describing our usage of certain terms and their role in the model, and then present the model itself. We then consider relevant experimental observations and certain testable implications of the model. Finally, some general implications of the model for evolutionary theory are mentioned.

Elements of the Model

The following definitions are intended only to clarify the usage of certain terms in our discussion of this model.

Gene: A region of the genome with a narrowly definable or elementary

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